Overview

- Mechanisms of ACL Injury
- Role of the Hip
- Failure of ACL by Ligament Fatigue
- ACL Tissue Engineering
ACL Injury: A Public Health Problem

- 400,000 ACL Injuries Annually in U.S. (350,000 Reconstructions) AOSSM Allograft Seminar (2006)
- Peak Age for Women – 14 yrs
- In the Most Vulnerable, Under Age 15 yrs
- Osteoarthrosis Approaching 70% within 10 yrs Ajuied (2014) AJSM
- Lifetime Cost of ACL Injuries Approaching $10 Billion/Yr Koenig (2013) JBJS

Injury Prevention is Crucial for Musculoskeletal Health

Prevailing Theory

Knee Abduction (Valgus) → ACL Injury
Hewett’s Valgus Hypothesis

205 female athletes
   Soccer, basketball and volleyball

• 9 ACL injuries:
   – 8.4 deg. ↑ knee abduction at initial contact (P<.01)
   – 7.6 deg. ↑ at max. (p<.01)
   – Valgus angles and moments – primary injury predictors

Hewett et al. (2005) AJSM

Hewett et al. 2005

1. Peak Knee Abduction Angle
   ACL Injured: 9°
   Uninjured: 1.4°
   Power: can’t be calculated
         (No S.D. given)

2. Knee Abduction Angle at Initial Contact
   ACL Injured: -5°
   Uninjured: 3.4°
   Power: can’t be calculated
         (No S.D. given)

Hewett et al. 2005

Peak Knee Abduction Moment
ACL Injured: -45.3 ± 28.5 Nm
Uninjured: -18.4 ± 15.6 Nm
Power: 69%
Problem: Values are not normalized to height and weight
**Inaccuracy of Skin Markers**

Skin markers vs. bone pins

<table>
<thead>
<tr>
<th>Knee Joint</th>
<th>Running (Reinschmidt)</th>
<th>Cutting (Benoit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add/Abduction</td>
<td>6.6° (RMS)</td>
<td>13.1° (absolute)</td>
</tr>
<tr>
<td>Int/External</td>
<td>7.9° (RMS)</td>
<td>5.4° (absolute)</td>
</tr>
<tr>
<td>Rotation</td>
<td>9.0° (RMS)</td>
<td>4.2° (absolute)</td>
</tr>
</tbody>
</table>

Reinschmidt et al. (1997) J Biomech
Benoit et al. (2006) Gait Posture

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**Bone vs. Soft Tissue**

Deneweth et al. Unpublished

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**Clinic Based Algorithm for ACL Injury Risk (pKAM)**

- Knee valgus motion (DVJ)
- Knee flexion range
- Tibial length
- Mass – Scale
- Quad/Ham strength surrogate
- 2-D video

Meyer (2011) BJSM
Meyer (2010) AJSM
Clinic Based Algorithm for ACL Injury Risk pKAM (Assessment)

- Nested Case Control Study – Evidence level 3
- Secondary analysis of DVJ data
- 1,855 H.S. and College female athletes
- Conditional logistic regression
- 20 ACL tears matched with 45 uninjured controls

Goetschius (2012) AJSM

Algorithm ACL Injury Assessment

Valgus (pKAM) did not predict noncontact ACL Injury

Goetschius (2012) AJSM

Landing Error Scoring System (LESS)

- Landing biomechanics during drop vertical jump (DVJ)
- Based on 17 point scale assessing lower extremity and trunk positioning on landing
- Frontal & Sagittal Video
- Max. flexion, global fluidity, ROM

Padua (2009) AJSM
Prospective Evaluation of LESS for ACL Injury Risk

- Case Control Study – Evidence level 3
- 3 years, 5047 (M & F) H.S. and College
- Conditional logistic Regression
  (LESS and ACL Injury Risk)

LESS did NOT predict ACL Injury Risk

Jump Video Analysis

Not Generalizable
Abduction vs. Internal Rotation?

Investigating ACL Injury Mechanisms

- In Vivo – Risky, Unethical!
- Screening at Risk Populations
  Surface Marker (?)
- Animal Models – Relevance?
- Cadaver Testing – Good Potential
  Must be Physiologic!
- Computer Modeling – can extend laboratory experiments

Fresh Insights on ACL Injury Mechanisms

2003 - 2017

Ed Wojtys
James Ashton-Miller
Tom Withrow
Youkeun Oh
David Lipps
Mélanie Beaulieu

Orthopaedic Surgery / Mechanical Engineering
Novel Cadaver Testing System

- Unconstrained knee
- Impact – (4-5 BW) in 50 msec
- Varus/valgus, int/ext rotation, flex/ext.
- Kinematics and forces monitored
- Realistic muscle forces

Normalized AM-ACL Relative Strain

What Happens to ACL Strain during Internal Tibial Rotation?
What Happens to ACL Strain during Internal Tibial Rotation?

ACL controls internal tibial rotation as well as anterior translation

ACL Size and Knee Structure Provide Insights on the Gender Difference in Peak ACL Strain
Structural Anatomy Matters!

Role of Larger Lateral Tibial Slope

Large compression force causes...

Internal tibial rotation

ACL Cross-Sectional Area, Lateral Tibial Slope and Medial Tibial Depth Geometry Provide Insights on the Gender Difference in Peak ACL Strain

David B. Lipps, Ph.D.
Youkeun Oh, Ph.D.
James A. Ashton-Miller, Ph.D.
Edward M. Wojtys, M.D.
ACL Strain – higher in Females

Lipps (2012) AJSM

Hip Range of Motion
an ACL Injury Risk Factor

Lipps (2012) AJSM
NFL Combine 2012

324 Athletes
(34 Reconstructed ACL’s – 10.5%)
Decreased Int. Rot. 

Bedi (2015) KSSTA

30° Decrease Int. Rot. 

ACL (18) 4.06x
ACL (18) 5.29x

Hips Internal Rotation (°)

Odds of ACL Injury

Bedi (2015) KSSTA

Hip Rotation & ACL Injury

Beaulieu (2015) AJSM
Beaulieu (2014) AJSM

Oh from Bedi (2015) KSSTA

**Single High Force Event**

? vs. ?

Repetitive Loading Injury (Ligament Fatigue)
ACL Injury

NFL Celebration Injury

First Evidence that ACL Rupture can be a Repetitive Loading Injury

Lipps (2013) AJSM
**Partial ACL Tears**

95% in Proximal 1/3 of ACL

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**Tissue Sample Sectioning**

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Fibrocartilage: Femur > Tibia

Femoral Enthesis

Tibial Enthesis

Beaulieu (2015) JOR

Enthoseal Angle: Femur < Tibia

Beaulieu (2015) JOR

a

b

No repetitive loading, with evidence of impactions due to early loading

ACL

Repetitive loading (n=128) with monosynaptic damage without gross ligament failure

Repetitive loading (n=45) with gross ligament failure (partial tear of PL, fibers an anthesis)
Summary

1. Mechanism of Injury
   Direction of Loading
   Monitor Cycles with Devices
2. Physical Exam of Hip
   (Pre-Participation)
   Limited Internal Rotation
   High Risk ACL Injury
3. ACL Fatigue Failure – Time Interval
   Intervention
   Rest-Recovery

Final Comment

While both increase ACL strain, an internal tibial torque induces a higher strain in the ACL than a knee abduction moment.
Funding Sources

- U.S. Department of Health and Human Services
- National Institutes of Health
- National Institute of Arthritis and Musculoskeletal and Skin Diseases
- National Football League
- Michigan Inst. for Clinical Health Research
- Coulter Foundation

Thank You
On The Fatigue Life of the Anterior Cruciate Ligament During Simulated Pivot Landings

Repetitive Loading

Micro damage Accumulation

Injury Prevention

Injury Mechanisms

ACL Injury → Uncertain Outcomes

Return to sports? Long term osteoarthritis!
Summary 1

• Tibial rotation is a major determinant of ACL strain.
• Tibial anatomy helps determine susceptibility to ACL strain.

ACL Injuries

1. Internal Axial Tibial Rotation
2. Ligament Fatigue-Partial Tears
3. Hip Predisposition
Unique dependent relationship

The Hip Joint & ACL Injuries

Odds of ACL Injury

Hip Internal Rotation (°)

Bedi (2015) KSSTA
Oh from Bedi (2015) KSSTA

ACL Injury Course

Jere working on shortening clip!
Molley (2011) BJSM

Greatest cause of disability after 18 years of age (twice that of cardiac disease)

The knee is the most common location!
**ACL Reconstruction Strategies**

Unmatched biomechanical properties of patellar tendon (or hamstring) graft and native ACL.

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**Tissue Engineering**

**Faculty**
- Lisa Larkin
- Ellen Arruda
- Deneen Wellik
- Ed Wojtys
- Tatiana Kostrominova

**PhD’s**
- Mike Smietana
- Jinjin Ma

**Student/Co-Author**
- Vasudevan Mahalingam

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**Tissue Engineered Bone-Ligament-Bone Scaffold Free Constructs for Sheep ACL Reconstruction**

Stimulates Growth of Normal ACL Tissue

ACL Growth & Remodeling with Time (40+ Sheep ACL Reconstructions)

Cellular Growth, Vascularization and Re-innervation Similar to Native ACL

Functions Like Uninjured ACL

Recreates More Normal ACL Function
- Not Produced with Current Procedures-

Frank R. Noyes, M.D.

- Kappa Delta Award – 1977
- Founded Cincinnati Sports Medicine
- AOSSM Hall of Fame
- Mentored 175 Sports Medicine Fellows
James Ashton-Miller, Ph.D.

• The Albert B. Schultz Collegiate Research Professor in Mechanical Engineering
• Distinguished Research Scientist
• Associate Vice President for Research
• Outstanding Colleague and Friend
• Together Published 27 Papers, Mentored 4 PhD Students

Orthopaedic Research Lab

Biomechanics Research Lab

PhD’s

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
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<tr>
<td>Tom Withrow, PhD</td>
<td>2005</td>
</tr>
<tr>
<td>Youkeun Oh, PhD</td>
<td>2011</td>
</tr>
<tr>
<td>David Lipps, PhD</td>
<td>2012</td>
</tr>
<tr>
<td>Mélanie Beaulieu, PhD</td>
<td>2014</td>
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</tbody>
</table>
Kappa Delta Sorority

Family

Wojtys’  Ashton-Miller’s

Go Blue!!!